

MSc Motorsport Engineering

Laser Doppler Vibrometer Brake Disc Modal Analysis

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Abstract

A laser doppler vibrometer (LDV) was used to perform a harmonic modal analysis on a brake disc. The study investigated the operating principles of an LDV testing setup and provided a practical methodology for its implementation. The results showed a series of harmonic resonant modes, distinguished by differing frequency peak magnitudes. The most significant responses included a second-order bending moment in the second band, a torsion mode in the third band, a second-order torsion in the fifth band, a first order bending harmonic mode in the first band, and a folding mode in the sixth band. Other observed harmonic modes exhibited comparatively minor responses.

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Laser Doppler Vibrometry

LDV System Operation

The laser doppler vibrometer operates via the doppler effect. The doppler effect is a change in a wave in relation to the relative velocity of the wave source and observer, which is expressed in the below equation.

$$f_D = f \frac{2 \times n \times v}{\lambda}$$

The doppler effect results in a reduction in wavelength as a wave source moves towards an observer, and an increase in wavelength when the source moves away from an observer (Castellini, Paone, & Pietroni, 2020). This change is proportional to the relative velocity of the source and observer, and thus the wavelength difference can be measured to determine the relative velocity .

LDV systems use a laser's light waves to assess the frequency shift of a surface using a reflected laser beam. A laser beam is first split into a reference beam and a measurement beam, and following this the measurement beam is trained on the sample, which reflects the beam. This reflected beam is again deflected and merges with the reference beam onto the detector.

The bragg cell is used to differentiate between where the sample moves towards or away from the laser, as otherwise these movements produce a signal that makes it difficult to differentiate this movement. The bragg cell generates a modulating frequency at 40MHz, which results in a change in output when the sample is stationary or moving towards or away from the sensor (Polytec, n.d.), allowing for greater fidelity in measurement. This is known as a heterodyne approach to LDV measurement, compared to a system lacking a bragg cell being a homodyne approach (Eichenberger & Sauer, 2021). This heterodyne setup is shown below.

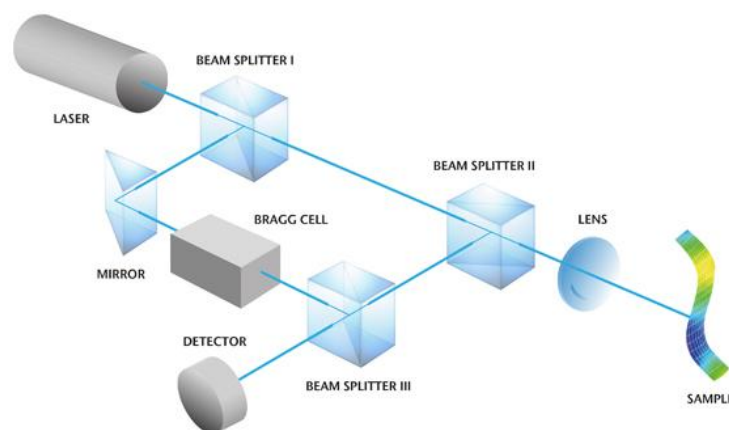


Figure 1 - Principle of laser doppler vibrometer (Polytec, n.d.)

Limitations

This method of study has some limitations. One way in which it is limited is that the surface quality of the specimen can affect the measured result, which is especially pertinent in this study, as the specimen is a used brake disc's friction surface being measured in this instance. This surface has significant roughness due to the friction from use. Surface quality of a specimen is a drawback to this form of study as it causes scattering in the light emitted by the laser, which is then picked up in the system's photodetector (Martarelli & Ewins, 2005).

Another drawback to the LDV approach is that testing is limited by line of sight, with a relatively large laser detector that must be positioned facing a specimen. This means that using LDV testing on complex geometry or in situ is much more difficult, or often impossible.

Measurements should also be made in an environment with relatively controlled lighting, given the detector's photosensitivity. Measuring in low-light conditions results in more noise, and so can affect the accuracy or resolution of the measured data (Rembe & Mignanelli, 2020). This can be mitigated by use of a more powerful laser, however high-powered lasers present a greater danger to the operator.

Finally, simply the price of the hardware can be prohibitively high for many companies to consider, as it can be upwards of \$30,000 (SIMTRUM, 2025). This results in companies choosing other methods to analyse resonance.

Literature Review

Laser doppler vibrometry is used across a range of scientific and engineering disciplines, with automotive engineering being one of these fields (Rothberg, et al., 2017). It is favoured for its non-destructive, non-invasive properties. The investigation of radial vibration is of particular interest in automotive applications for powertrain design, drive spindles, tooling, and so on, where parts are rotated at high RPMs, resulting in significant vibration (Halkon & Rothberg, 2004). These parts are at greater risk of stresses relating to this vibration, and so must be analysed for the purposes of safety and reliability, as well as performance as to how far these parts can be pushed before they fail. This type of analysis is also carried out for the purpose of sound deadening, increasing comfort in the commercial automotive industry (Junge, 1994). Experimental modal analysis is also an area where SLDV can be very important (Ewins, 2000). In this area, parts are tested in order to create an experimentally informed theoretical model of their vibrational behaviour (Ewins, 2000). LDV systems can also be used to measure vibrations with the purpose of detecting damage in used parts, as an NDT technique (Tavares, et al., 2024). Tavares et al use the LDV system to detect damage in carbon-fibre reinforced polymer (CFRP) specimens, combined with machine learning approaches to data analysis, showing that LDV experiments still holds a place at the forefront of vibrational investigations in the automotive sector.

Procedure

Apparatus

- Laser Doppler Vibrometer
- Brake Disc
- Solenoid
- Vice

Introduction

The experiment aims to identify a component's main harmonic resonant modes and shapes, using a laser doppler vibrometer. The machine uses a mesh to measure the vibration at each point, approximating the overall movement of the part caused by vibration.

Method

The brake disc was clamped into place using the vice. The solenoid was set up at the correct distance from the back face of the brake disc. It was placed close enough to excite the sample and cause vibration, but far enough that it will not push itself away from the brake disc in the vice, as the solenoid was free standing.

The laser was calibrated to focus at the distance of the sample surface, ensuring the laser's measurement accuracy. An incidence angle of 65 degrees was used.

The mesh was created within the software, where each point would be measured to give an approximation of the vibrational modes of the sample. This mesh is shown below.

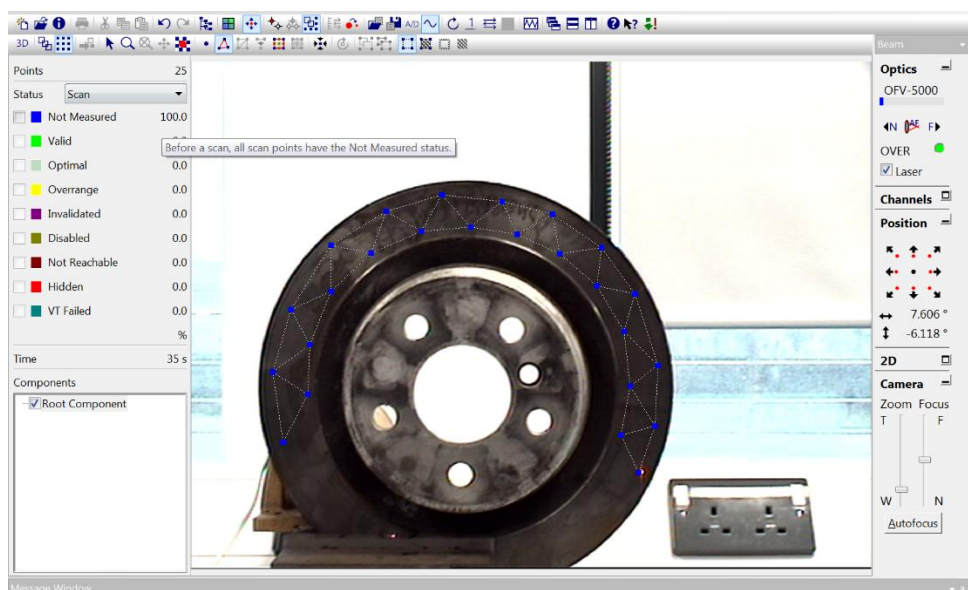


Figure 2 - Created Mesh for the first run

Two test runs were then carried out, with the brake disc being moved between each one, to see how this would effect the results. The mesh for the second test is shown in the figure below.

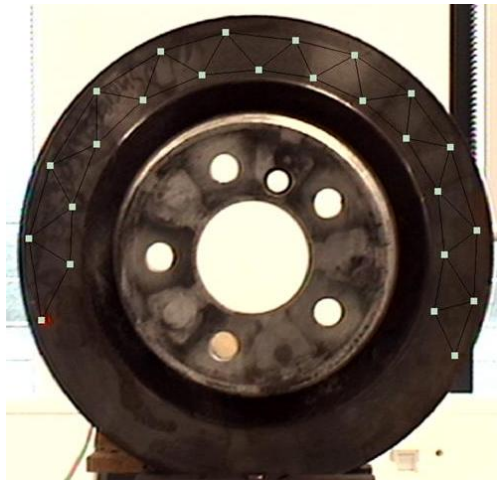


Figure 3 - Mesh for the second run

This study is limited by a relatively coarse mesh, making higher order harmonic frequencies more difficult to visualise. If the test could be carried out again with, a finer mesh would be used to ensure greater fidelity in the calculation.

The data was collected via a series of screenshots visualising displacement, and plots showing the peaks in frequency. The full data can be found in the appendices of this report, however these figures are copied into the discussion of the results where appropriate to provide a visual aid for the analysis.

Results and Discussion

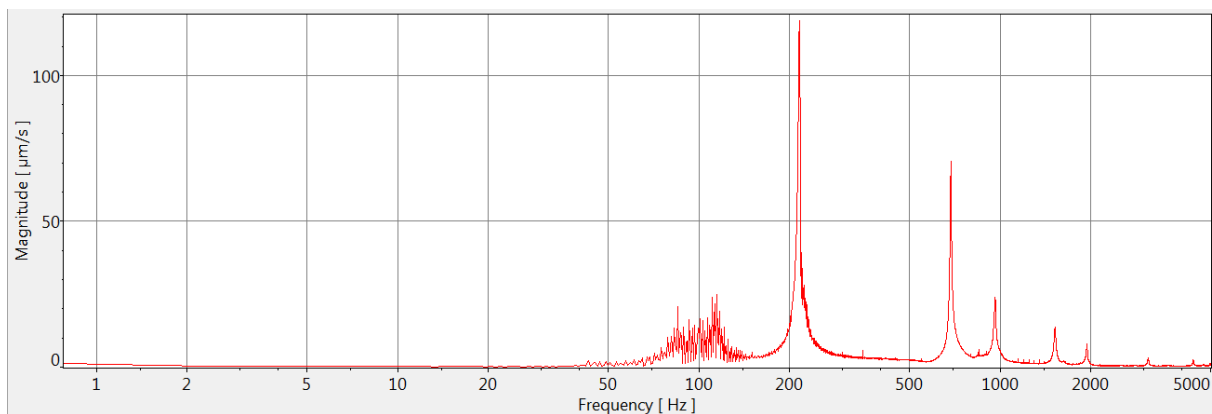


Figure 4 – Scan 1 Range of Peaks

The above figure shows the range of peaks for the first scan carried out. A noisy first peak can be seen at 114.8Hz, and a second clear peak around 215.6Hz. Subsequent peaks up to band 9 can be seen at 686.7Hz, 963.3Hz, 1523Hz, 1943Hz, 3106Hz, and 4380Hz. The magnitude of these peaks decrease as frequency increases.

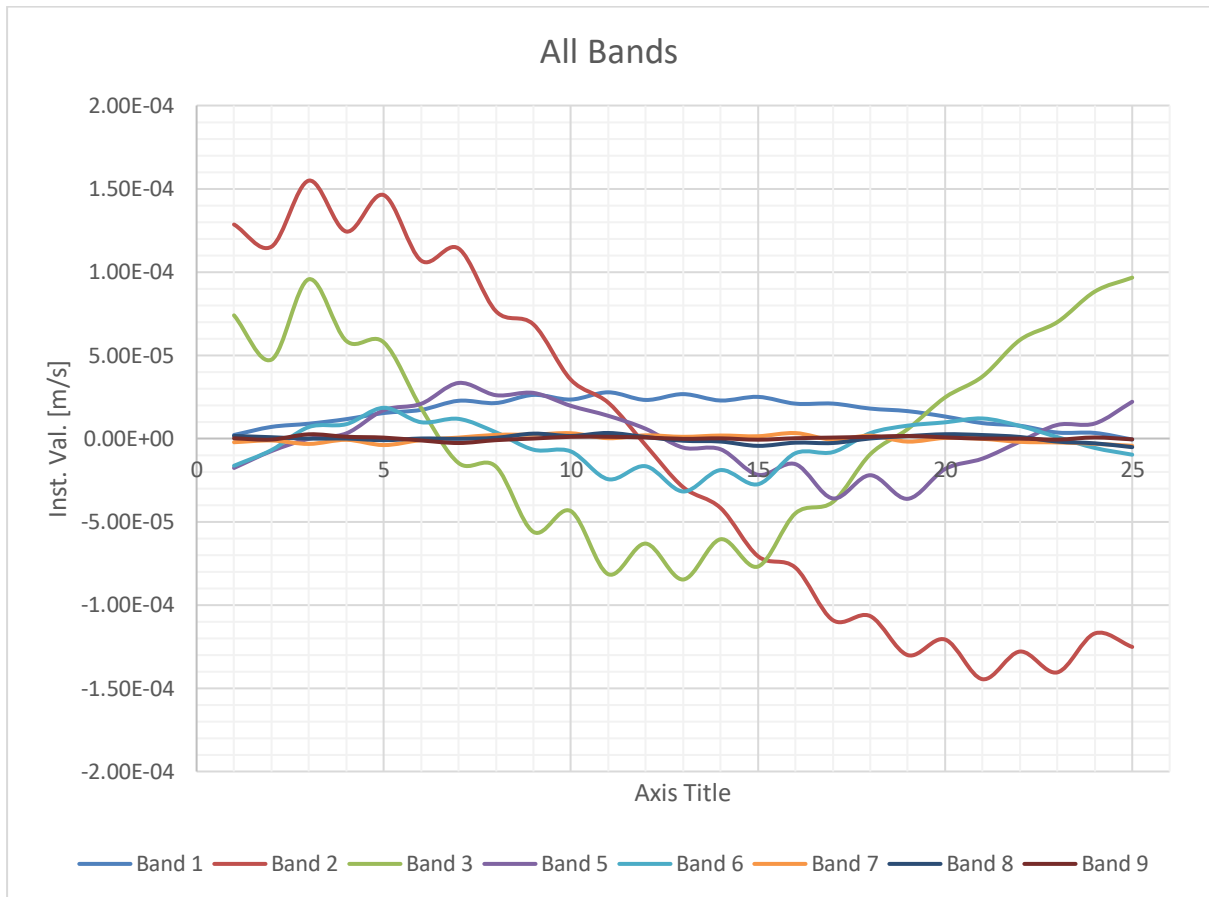


Figure 5 - Scan 1 all bands

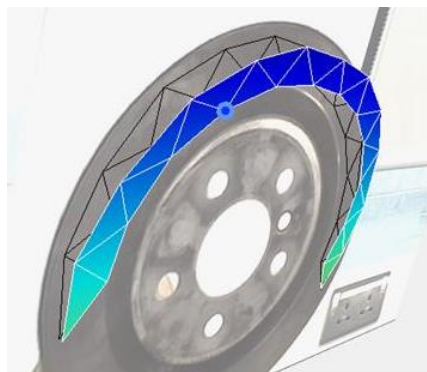


Figure 6 – Scan 1 Mode 1

This screenshot shows the brake disc's fundamental frequency, the lowest frequency waveform, extracted from the first peak of the overall range above. Here the displacement visualisation is quite smooth, showing that the mesh has enough fidelity to effectively show this frequency. The displacement visualisation shows a simple first order bending moment horizontally across the part, where the bottom side of the disc would be coloured in red, moving behind the 2 dimensional image. This simple bending can also be seen in the plot, which can be more clearly seen in the individual plots in the appendices.

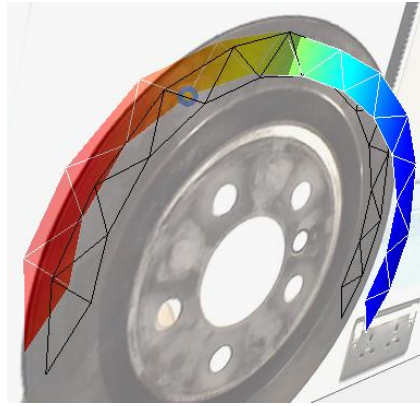


Figure 7 – Scan 1 Mode 2

A second order bending moment can be seen over the second band, akin to a sine wave, which is once again reflected in the plot. This band has the greatest range of magnitude by a significant margin over the majority of the other resonant modes, along with band 3 as well, however this is still roughly half the magnitude.

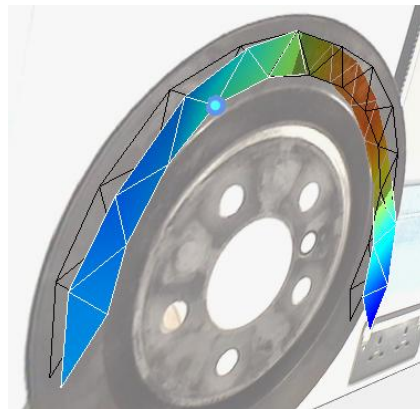


Figure 8 – Scan 1 Mode 3

Torsion can be observed in band 3, to a relatively high magnitude like as mentioned before. It can be seen here that the visualisation is beginning to appear more choppy, with colours beginning to change sharply at mesh edges. This further indicates that a finer mesh would benefit the results of the study.

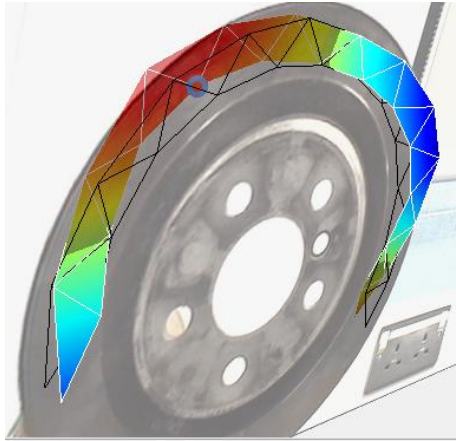


Figure 9 – Scan 1 Mode 5

A second order torsion moment appears to be the most likely mode of resonance in this band.

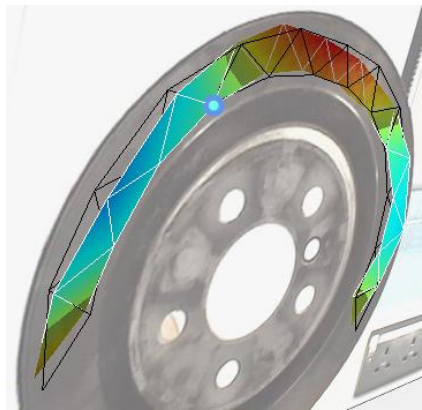


Figure 10 – Scan 1 Mode 6

Given the darker colouration towards the edges of the displacement plot, a folding moment appears to be most accurate for this harmonic mode. The coarseness of the mesh makes this difficult to visualise.

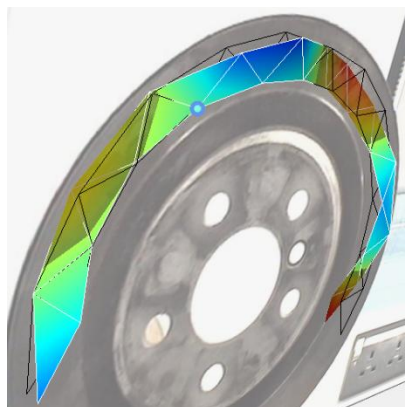


Figure 11 – Scan 1 Mode 8

A second order folding moment appears most accurate here, given the same outer colouration and increased bend complexity.

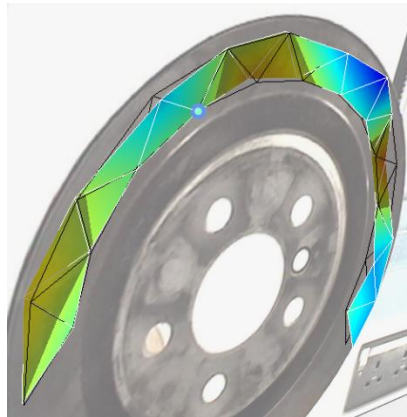


Figure 12 – Scan 1 Mode 9

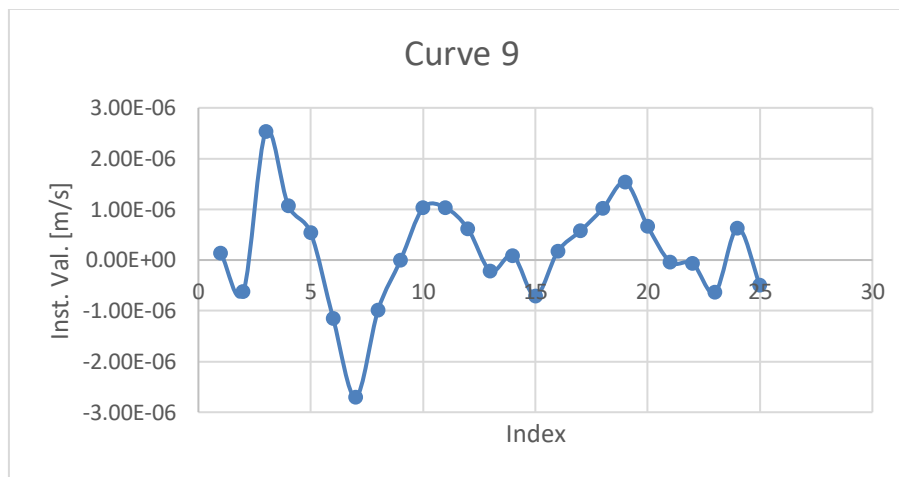


Figure 13 - Scan 1 Curve 9

This band appears to be a rippling or folding effect, but the mesh coarseness makes this mode difficult to identify. The plot also shows some curvature but there is significant variation and noise, making averaging some kind of curve difficult to impossible given the fineness of the mesh used.

Furthermore however, it should be noted that only the first 5 harmonic modes hold significant magnitude when compared to each other, and so these are the most important resonant frequencies to consider when making provision for stresses arising from this movement.

Conclusion

To conclude, a laser doppler vibrometer was used to carry out a modal analysis on a brake disc. The operating principle of an LDV testing setup was explored, and the practical method was also explained. The brake disc was found to have a series of major and minor harmonic resonant shapes, given the difference in magnitude of the frequency peaks. The greatest magnitude was a second order bending moment in the second band, followed by a torsion mode in the third band, a second order torsion in the fifth, a first order bending mode in the first band, and a folding mode in the sixth. The remaining harmonic modes identified were comparatively minor, and these results were validated in a second scan.

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Appendices